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HIGH-TECH METALS IN BRITISH COLUMBIA

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FOREWORD

Recent technological breakthroughs in the fields of ceramics, medicine, aerospace engineering and electronics, in particular the areas of computers and superconductors, are creating new uses for a variety of rare and minor metals. These include zirconium (Zr), hafnium (Hf), yttrium (Y), rare-earth or lanthanide elements (REE), germanium (Ge), gallium (Ga), niobium (Nb), tantalum (Ta) and beryllium (Be). As a result, there is now considerable interest in economic deposits of these metals, however, most geologists and prospectors are unfamiliar with these commodities and the geological environments in which they occur.

With the exception of a minor amount of byproduct recovery of gallium and germanium from Cominco's Trail smelter, none of these metals is currently produced in British Columbia. The purpose of this Information Circular is to increase awareness of these commodities and to provide the background information which will hopefully lead to new discoveries of these resources.

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INTRODUCTION

"HIGH-TECH" ELEMENTS - WHAT ARE THEY AND WHERE ARE THEY FOUND?

The "high technology" metals include a number of rare and minor metals that have highly specialized applications in a wide range of industries. Although uses of the individual metals are numerous and diverse, in general, only very limited quantities are consumed. The demand for many of the "high-tech" metals is expected to increase significantly in the near future, due in part to recent technological innovations.

Metals which are considered to have "high-tech" applications include zirconium (Zr), hafnium (Hf), yttrium (Y), rare-earth or lanthanide elements (REE), germanium (Ge), gallium (Ga), niobium (Nb), tantalum (Ta) and beryllium (Be). Significant increases in the consumption of high-technology metals have been projected as follows (Bernstein, 1986; Richardson *et al.*, 1989):

INDUSTRIAL SECTOR	METALS
Nuclear	Nb, Zr, Hf, Be, REE
Aerospace	Be
Specialty Steel	Nb , REE
Electronics	Ga, Ge, Ta, Be, Y
Glass/ceramics	Zr, Y, Be, REE
Medicine	Ge

It should be mentioned that because of special uses and small quantities involved only some of the sources for "high-tech" elements are marketed in mineral concentrates (zircon, rare-earth minerals, niobium minerals and beryl). The rest, if warranted are recovered as by-products or co-products and marketing is entirely in hands of refiners or processing companies. Therefore the producers of concentrates may receive bonus, if the values of "high-tech" elements are high enough to be of interest.

BERYLLIUM

USES

Beryllium, since the 1920s, has become an important industrial metal because of its high strength, rigidity, extremely light weight and thermal conductivity. It is used predominantly in three forms: alloys, in particular beryllium-copper alloys; as beryllium metal; and as beryllium oxide or beryllia ceramics.

Beryllium-copper alloys, which contain an average of 2.0 per cent beryllium, represent an estimated 65 per cent of beryllium consumption; they are used in industries such as aerospace, computers, electronics, defense, oil and gas exploration and telecommunications. Beryllium-copper alloys are used in miniaturized spring elements and chill plates in computers, aneroid barometers, connectors and contacts for a wide range of electronic applications, as well as for switch-gear, relays and other electrical equipment. The aerospace industry uses the alloys in aircraft frames and bearings, and satellites and space vehicles. High-strength, noncorrosive housings for underwater cable stations and telephone repeaters are also made of beryllium-copper alloys, as are dies, molds for plastics, high-strength nonsparking tools, tubing used in the oil industry to house down-hole instruments, and diaphragms for a wide range of measuring instruments.

Approximately 20 per cent of consumption is as beryllium metal, which is used primarily in the aerospace and defense industries. It is used in heat shields, rocket motors, aircraft and space-shuttle brake discs, inertial navigational systems and in special mirrors for infrared satellite surveillance systems. Beryllium metal is used in the defense industry in the fabrication of military targeting systems and inertial navigational systems in submarines, and also as a shield material around the inner core of some nuclear fission reactors. Beryllium is virtually transparent to X-rays and therefore used in the manufacture of X-ray windows for research and medical equipment.

Beryllium oxide ceramics account for approximately 15 per cent of consumption. They are used predominantly in electronic applications such as substrata for electronic circuits, insulators and heat sinks, as well as in the fabrication of microwave radar devices and lasers. Beryllium oxide is also used in the manufacture of other beryllia compounds (Kramer 1990, 1987; Petkof, 1985a; Taylor, 1987). In 1989, the USA consumption of beryllium was 260 tonnes valued at approximately US $125 million.

OCCURRENCE-GEOLOGICAL SETTING

Beryllium occurs as an essential constituent of approximately 40 minerals, the most common of which are beryl, bertrandite, phenacite, beryllite and chrysoberyl, and as an occasional or minor component in 50 other minerals. The two main geologic environments in which it occurs are volatile-enriched granite systems and peralkaline granite-syenite complexes.

Beryllium, commonly in the form of beryl, occurs in zones, filled fractures and replacement bodies associated with heterogeneous granite pegmatites. These pegmatites, which may also contain lithium minerals, commonly are late-stage differentiates of volatile-enriched or "specialty" granites. Beryllium is also concentrated in quartz-greissen veins and skarns related to volatile-enriched granites which often also carry other elements such as tin, tungsten, fluorine, and occasionally molybdenum. Topaz rhyolites, which are the extrusive equivalent of volatile-enriched granites may also contain or be associated with beryllium mineralization, in some cases containing the mineral bertrandite.

Peralkaline granite-syenite complexes sometimes contain significant accumulations of beryllium. They generally consist of multiphase intrusions, with beryllium minerals such as phenacite and bertrandite concentrated in late-stage intrusions and pegmatites. Commonly, other 'high-tech' elements such as niobium, rare earths, yttrium and zirconium are associated with beryllium in these deposit types.

Beryl is known to occur in pegmatites in a number of areas of British Columbia including the Horseranch Range, near Cassiar and the Skookumchuck Creek and Hellroaring Creek areas in the Kootenays (Mulligan, 1968). Beryllium-enriched skarns occur at Ash Mountain and Needlepoint Mountain in the Cassiar district. Altered tuffs associated with topaz rhyolites are mined for beryllium at Spor Mountain in Utah; similar occurrences have not been documented in British Columbia. There has been no documentation of peralkaline granite-syenite systems in British Columbia. Significant prospects of this type occur at Thor Lake, in the Northwest Territories (Trueman, 1989) and at Strange Lake and Seal Lake in Labrador (Miller; 1986, 1988).

ECONOMICS

The principal world producers of beryllium ores are Brazil, China, the U.S.S.R. and the United States. In 1989,

approximately 380 tonnes of beryllium metal was produced worldwide. At that time, beryllium oxide powder sold for $61.35US per pound; beryl ores containing 1 per cent BeO were quoted at $78 to 85US per short ton (Kramer, 1987).

At Spor Mountain, Utah, altered tuffs which are, overlain by topaz rhyolites, contain approximately 1 to 2 per cent of the mineral bertrandite, a hydrated beryllium silicate [$Be_4Si_2O_7(OH)_2$]. The ores reserves in this deposit are in the order of 4.85 million tonnes grading 0.56 to 0.60 per cent BeO, with a cut-off grade of 0.30 per cent (Griffiths, 1985) are currently being mined. High-grade beryllium ores, containing as much as 11 per cent BeO, in the form of mineral beryl, are mined in Brazil.

The Thor Lake deposit, in the Northwest Territories, is a beryllium prospect in which two zones have been identified, one containing approximately 497 000 tonnes of ore grading 1.4 per cent BeO and the other with 1.3 million tonnes of 0.66 per cent BeO; the ore mineral is phenacite, a beryllium silicate [Be_2SiO_4].

The beryl ores are more difficult and expensive to process than ores containing bertrandite or phenacite. Processing Spor Mountain ore and beryl concentrate are cost comparable (K. Paulson, 1990; personal information).

GALLIUM AND GERMANIUM

USES

Gallium is used primarily in the manufacture of semiconductive compounds such as arsenides, aluminum arsenides, arsenic phosphides, indium arsenides and phosphides. The bulk of consumption is in the production of opto-electronic devices and integrated circuits. Opto-electronic devices such as light-emitting diodes (LEDs), photodiodes, laser diodes and solar cells (photovoltaic devices) take advantage of the fact that gallium arsenide compounds can convert electrical energy to optical energy (light) and vice versa (Kramer, 1988). Opto-electronic devices are used primarily in nonmilitary applications such as communication systems (fibre optics) and consumer electronic products (radios, televisions, stereo systems, compact-disc players, laser printers, visual displays in calculators, *etc.*). Gallium arsenide based integrated circuits are used as logic and memory elements in computers and in equipment to process electronic signals produced by radar, military defense systems and satellite communications systems. In these applications, gallium arsenide is used in place of silicon semiconductor chips because it has the ability to send information approximately five times faster, can operate at higher temperatures and withstand more radiation than its silicon-based counterparts (Kramer, 1988). Gallium can also be alloyed with vanadium or nickel to produce superconductive materials. Other uses are in dental alloys as a substitute for mercury, in indium-tin alloys used for sealing glass windows in vacuum systems and as a constituent of cadmium, titanium or magnesium alloys (Petkof, 1985b).

In the late 1970s it was discovered that germanium metal, as well as some germanium alloys and glasses, is transparent to infared radiation having wavelengths longer than 2 micrometres. Since then the principal use of germanium has been in infrared optics. It is used to produce camera and optical lenses, microscope objectives, beam splitters, partial transmitters and windows that can transmit and focus infrared radiation onto film or electronic detectors. The principal applications are: night-viewing scopes on aircraft and other military equipment and for guidance systems on missiles and aircraft; night, fog or smoke-viewing equipment used by police, fire fighters, and others; satellite-mapping equipment; medical diagnostic equipment; 5) heat-loss monitoring equipment and; heat or radiation detecting devices, for example fire alarms. Glass-fibre light guides for long-distance telecommunication systems also use a germanium compound as a major constituent of the optical core. Other uses of germanium include catalysts for the production of polyester fibres and plastics used in the fabrication of food and drink containers, and phosphors or colour modifiers for fluorescent lighting. Research into the use of organo-germanium compounds in pharmaceuticals (drugs) has produced favorable results; certain compounds have been useful in the experimental treatment of some cancers, viral infections and auto-immune diseases such as arthritis (Bernstein, 1986; Plunkert, 1985).

OCCURRENCE-GEOLOGICAL SETTING

Gallium is more abundant in the earth's crust than antimony, silver, bismuth, molybdenum or tungsten, and only slightly less abundant than lead, however, it is rarely concentrated into rich deposits like these elements. It has chemical similarities to aluminum and, to a lesser extent, ferric iron. In different environments it can be lithophile, or to a lesser extent, chalcophile, siderophile and organophile. Most highly aluminous rocks and minerals, and some zinc minerals, contain detectable amounts of

Figure 1. Anomalous gallium and germanium in western North America.

gallium. The main deposit types in which gallium is concentrated are: bauxite deposits, particularly those formed from nepheline syenites and related alkaline rocks; low to moderate temperature, sphalerite-rich sulphide deposits in sedimentary rocks (*e.g.* 'Mississippi-Valley' type lead-zinc deposits) or in zinc-rich volcanogenic massive sulphide deposits; copper-rich sulphide deposits, particularly sedimentary breccia pipes (solution-collapse breccia), and the oxidized zones of these deposits; and rare metal deposits associated with metasomatism and late-stage, highly alkaline or peralkaline granite-syenite intrusions. In bauxite deposits, gallium substitutes for aluminum; in zinc deposits, it substitutes in the sphalerite lattice or may be present in accessory minerals such as germanite, a complex copper-iron-germanium sulphide. In copper deposits, it is present in sulphides and sulfosalts, generally substituting for iron, and in the oxidized portions of these deposits it generally occurs in jarosite-group minerals and limonite. In alkaline-peralkaline deposits it commonly substitutes for aluminum in albite or, occasionally, in micas (Bernstein, 1986; Petkof, 1985b; Tekverk and Fay, 1986).

Germanium is just below silicon in the Periodic Table and for a long time was believed to have the same chemical behaviour. However, while germanium is dispersed in silicates in amounts of a few parts per million, it behaves differently in a number of environments. Like gallium, it can be a lithophile, chalcophile, siderophile or an organophile element in different environments. Germanium has a mean crustal abundance of approximately 1.5 ppm. It is enriched in a number of geologic environments, many of which also contain concentrations of gallium. As with gallium, it is concentrated in sphalerite-rich sulphide deposits, particularly low-temperature sediment-hosted deposits and copper-rich sulphide deposits, particularly those in sedimentary hostrocks and associated with high arsenic, antimony and tin levels (copper-rich breccia pipes) and the oxidized portions of these deposits. Germanium may also be concentrated in coal and lignite, and in iron oxide deposits (Bernstein, 1986; Plunkert, 1985). In zinc-rich sulphide deposits, it is concentrated in sphalerite or, rarely, occurs as germanite inclusions within the sphalerite. In copper-rich sulphide deposits, germanium occurs in its own sulphide minerals or in sulfosalts, substituting for arsenic, antimony or tin. In iron oxide deposits and the oxidized zones of copper deposits, germanium is concentrated in hematite and goethite; in the oxidized copper deposits it may also occur in hydroxide, oxide, sulphate and arsenate minerals. In coals, it is bound to organic compounds (Bernstein, 1986).

In British Columbia, a number of the potential gallium and germanium-bearing deposit types are unknown and unlikely to occur. There are no bauxite deposits in the province, the geologic processes required to produce them have never occurred. Alkaline granite-syenite complexes have not been found, nor have copper-rich sedimentary breccia pipes, although no reason exists for their absence. Alkaline granite-syenite complexes, such as Thor Lake, N.W.T., are known to contain significant amounts of gallium; copper-rich breccia pipes are mined for gallium and germanium at Tsumeb, Namibia and the oxidized zone of a similar pipe in Utah (the Apex mine) was in production in 1986-87 and again since 1989. Iron oxide deposits (magnetite skarns) and coals are well known in the province, but, in most cases have not been evaluated for gallium or germanium, with the exception of coals at Lang Bay, near Powell River, which reportedly contain approximately 70 to 140 ppm GeO_2 (White, 1986). The best potential for gallium and germanium in British Columbia lies in sediment-hosted zinc deposits; the carbonate-hosted deposits in the Robb Lake belt, northeastern British Columbia are known to contain anomalous amounts of gallium and germanium and one showing, the Cay prospect contains world-class levels (Leighton *et al.*, 1989).

ECONOMICS

Gallium is currently recovered during the refining of bauxite to aluminum, in which it is present in concentrations in the 50-ppm range, and during the smelting and refining of sphalerite concentrates containing 50 to 200 ppm gallium. Germanium is principally recovered during the smelting of zinc concentrates containing between 80 and 260 ppm germanium. 'High-grade' ore from the St. Salvy zinc mine in France contains 600 to 800 ppm germanium. Gallium and germanium are also recovered from copper-rich, sediment-hosted breccia pipes. In this type of deposit high-grade zones run 5 to 7 per cent germanium and 0.5 per cent (5000 ppm) gallium, while most ore contains 50 to 500 ppm germanium and 10 to 200 ppm gallium (Bernstein, 1986; Leighton, personal communication, 1988).

The world's main producers of gallium are Japan, France, Germany, Canada and China and the major producers of germanium are the U.S.A., Belgium, France and Italy, Germany, the U.S.S.R., eastern Europe and China. In these countries, production is from bauxite and zinc ores mined locally and imported. The world production of gallium is in the order of 40 000 kilograms per year and the production of germanium is around 82 000 kilograms per year. The price for both elements, at 99.9999 per cent purity is in the order of $525US per kilogram for gallium and $1.060US per kilogram for germanium. The demand for both elements is considered by experts to be increasing (Petkof, 1985b; Plunkert, 1985; Tekverk and Fay, 1986; Roskill Information Services, 1986) and some smelters are now willing to pay a premium for concentrates containing gallium, germanium and indium, if amounts warrant.

NIOBIUM AND TANTALUM

USES

Niobium, which is also referred to as columbium, is a metal used as an alloying element in the production of high-temperature specialty steels (high-strength, low-alloy, or HSLA steels) and superalloys used in heavy equipment, ships, structural steels and in nuclear, aerospace and pipeline applications. The addition of a small amount of niobium to steel helps control the grain size and thereby improves mechanical properties and strength-to-weight ratios. It also improves the heat resistance of steel which allows its use in gas and steam turbine engines, aircraft and aerospace power systems and heat shields on rocket nozzles. Niobium also has important potential as a superconductor of electricity at cryogenic temperatures (Griffith, 1970).

Tantalum is a relatively rare, heavy, inert metal that is used in electronics, chemical processing equipment, metal-cutting tools and high-temperature steel alloys. Tantalum capacitors are used in solid-state circuitry for computer and communications equipment used in space, defense and industrial fields. It is also used in electronic tubes, battery chargers, transistors and voltage-surge arresters. Because of its resistance to corrosion and good thermal conductivity it is used extensively in chemical and metallurgical processing equipment and laboratory ware. Tantalum is completely inert to human body fluids and can therefore be used in numerous medical applications such as screws to hold bones together, surgical staples to close wounds, replacement joints and bone parts (Griffith and Sheridan, 1970).

OCCURRENCE-GEOLOGICAL SETTING

Niobium is the 33rd most abundant element in the earth's crust, which contains 24 ppm on average. The principal niobium-bearing mineral is pyrochlore, a niobium-titanium-calcium oxide, although other niobium-bearing species, such as columbite and fersmite, are also known. It is principally concentrated in carbonatites and related alkaline rocks; the Aley prospect in northern British Columbia is a good example of this type of deposit. To a lesser extent, niobium is also found in alkaline granite-syenite complexes, such as Thor Lake, N.W.T., associated with other 'high-tech' elements, or in pegmatites and tin deposits associated with volatile-enriched granite systems.

Tantalum is a relatively rare element, the 54th most abundant in the earths crust, where it has an average abundance of 2.1 ppm. It is generally associated with tin in skarns, greissens and pegmatites related to volatile-enriched granite systems. Tantalum is mined from the Tanco pegmatite, near Winnipeg, Manitoba. It also occurs in alkaline granite-syenite systems, as at Thor Lake, N.W.T. and Strange Lake, Labrador, and may also be present in carbonatites, generally in the mineral pyrochlore. In carbonatites and alkaline rocks the niobium/tantalum ratios commonly exceed 100, whereas in granitic rocks they average 4.8 (Currie, 1976). The exception are carbonatites in Blue River area, B.C. where niobium/tantalum ratio is 4.

Niobium occurs in all carbonatite complexes in B.C.; however, in most it is present in subeconomic concentrations, generally less than 0.3 per cent Nb_2O_5. The Aley carbonatite complex appears to have the greatest potential of any carbonatites so far discovered in this province. Work by Cominco Ltd. since 1982 has defined extensive zones containing between 0.66 and 0.75 per cent Nb_2O_5, and localized areas containing in excess of 2 per cent Nb_2O_5 (K. Pride, personal communication 1988), grades that easily rival the Niobec deposit at St. Honoré, Quebec. In light of the current soft niobium market, this deposit is not currently being developed.

Tin-bearing mineralization is associated with specialty granites in northern British Columbia in the Cassiar district and in some areas in the south of the province, but little information is available on the tantalum potential of these rocks. No tantalum pegmatites are known in British Columbia.

ECONOMICS

The majority of the world's niobium is produced from carbonatites and residual weathered zones overlying carbonatite complexes. Approximately 85 per cent of total world production comes from Brazil, where pyrochlore has been concentrated by residual weathering to grades in the order of 3 per cent Nb_2O_5. In Canada, niobium is being mined by Niobec Inc. at St. Honoré, near Chicoutimi, Quebec, where grades are 0.5 to 0.67 per cent Nb_2O_5. Minor amounts are recovered as byproducts from placer tin placer mining in Nigeria. In 1988 and 1989 niobium concentrate (containing approximately 60 per cent Nb_2O_5 in pyrochlore or columbite) sold for $2.25 to 2.65US per pound, which was considerably down from the mid-1980s price of around $4.00US per pound.

Tantalum is principally recovered as a coproduct of mining, tin lodes, tin placers and beryllium-tin-niobium pegmatites (Griffith and Sheridan, 1970). The principal tantalum-producing countries are Zaire, Nigeria, Brazil, French Guiana, Mozambique, Thailand, Australia, Malaysia, South Africa and Canada. In 1989 tantalite sold for about $39US per pound of contained tantalium pentoxide.

Pyrochlore crystals from the Blue River carbonatite, British Columbia.

RARE EARTHS AND YTTRIUM

The rare-earths, or lanthanides, are a series of 15 elements, atomic numbers 57 to 71, that have somewhat similar chemical and physical properties and are therefore grouped together. Yttrium, atomic number 39, although not strictly a rare-earth element, is commonly grouped with them as its chemical properties are similar. The rare earths are divided into two subgroups, cerium and yttrium, indicated in the accompanying table.

USES

These elements are used principally in petroleum-cracking catalysts, iron, steel and other metal alloying agents, glass-polishing compounds and glass additives, permanent magnets and phosphors for television and lighting tubes (Hendrick, 1985). Mixtures of rare earths, such as mischmetal, are commonly used as catalysts and alloying agents. In other applications, pure rare-earth oxide compounds are used, as catalysts and alloying agents, commonly for example europium oxide to produce the red phosphor in colour television picture tubes and europium, yttrium and strontium oxides in fluorescent lights to emit a white light that has greater perceived brightness than conventional fluorescent tubes. Rare-earth permanent magnets, particularly samarium-cobalt and neodymium-iron-boron magnets are used in various electric motors, alternators, generators, line printers, computer disk-drive actuators, speakers, headphones, microphones and tape drives. The rare earths also have important potential usage in the fabrication of superconductors and applications in advanced ceramics and lasers (Wheat, 1987); erbium and holmium-doped lasers are used in eye operations and neodymium-doped yttrium-aluminum-garnets produce short wavelength laser beams that are used in cutting and scribing semiconductors and for drilling and welding.

OCCURRENCE-GEOLOGICAL SETTING

Rare-earth elements are concentrated in a number of different geological environments. They commonly occur in carbonatite and alkaline rock complexes. They are also found in skarns, pegmatites and veins associated with volatile-enriched granites; in alkaline granite-syenite complexes associated with other 'high-tech' elements; in heavy mineral beach placers; and in sedimentary phosphorites (particularly yttrium). Rare earths also occur in high-temperature, nontitaniferous magnetite deposits such as the Bayan Obo deposit in China. There is some dispute as to the nature of this deposit; it has been classified alternatively as a contact metasomatic deposit or as a metamorphosed carbonatite-related deposit. Yttrium is also concentrated in uranium paleoplacer deposits and has been recovered from uranium mines in Elliot Lake, Ontario . The most important deposit types are considered to be those related to carbonatite-alkaline complexes and beach placers (Hendrick, 1985; O'-Driscoll, 1988; Shannon, 1983).

In carbonatites, the rare earths are present mainly in the form of the cerium subgroup, or light rare earths. A considerable amount of rare-earth elements may be contained in common minerals such as calcite, dolomite, pyrochlore, fluorite, apatite, sphene and zircon. Rare earth-carbonate and fluorocarbonate minerals such as bastnaesite and parisite, or phosphate minerals such as monazite or xenotime may also be present in alkaline suites and host the rare earth elements. The Mountain Pass deposit in California, where rare earths are recovered from a bastnaesite-rich carbonatite, is one of the most important light rare earth producers in the world.

In beach placers, rare earths are generally contained in phosphate minerals such as monazite and xenotime or in silicates such as allanite. Most of these placers also contain other economically important heavy minerals such as magnetite, ilmenite and rutile.

In British Columbia, rare earths and yttrium are known to occur in association with carbonatites and alkaline rocks. Most prospects have not been extensively explored; selected samples from one area assayed as high as 14.5 per cent total rare-earth oxides (predominantly cerium and lanthanum) and from another area, samples contained up to 1.13 per cent yttrium oxide. The presence of these, and other, highly anomalous occurrences indicates that British Columbia is highly prospective for economic accumulations of carbonatite-related rare-earth elements. Veins and skarns are associated with specialty granites in northern British Columbia; these reportedly contain some rare earths, but have not been examined in any detail for these elements.

ECONOMICS

The U.S.A., Australia and China are the major producers of rare earths (Griffiths, 1984; Hendrick, 1985). Most of the economic recovery in the United States comes from the Mountain Pass carbonatite in California,

which grades 7 to 8 per cent total rare-earth oxides, predominantly of the cerium subgroup and has estimated reserves of 31 million tonnes. Bastnaesite is the principal ore mineral. In Australia, rare earths are recovered from monazite beach placers; in China rare earths occur in tabular magnetite deposits (Bayan Obo), in fluorite-quartz-carbonate and tungsten-quartz veins and pegmatites associated with volatile-enriched granites and in tin placers (Lee, 1970). India, Malaysia, Brazil and Thailand also recover significant amounts of monazite from beach placers.

At Thor Lake, N.W.T., an alkaline granite-syenite complex, an estimated 395 000 tonnes of 0.21 per cent Y_2O_3 is contained in one prospective ore zone together with significant beryllium.

World production of rare-earth minerals (concentrate) is in the order of 80 000 tonnes annually. Concentrate prices are approximately $1.05US per pound of bastnaesite concentrate containing 70 per cent rare-earth oxides; $800 to 900A per tonne of monazite concentrate with a minimum of 55 per cent rare-earth oxides, f.o.b. Australia; and $32 to 33US per kilogram for yttrium mineral concentrate (xenotime) with 60 per cent yttrium oxide, f.o.b. Malaysia. Refined rare-earth oxides, as quoted by Molycorp in January of 1987, vary in price from a low of $4.50US per pound for cerium oxide to $750US per pound for europium oxide and $1000US per pound for thulium oxide. Prices for yttrium, gadolinium and samarium oxides are in the range of $50 to 55US per pound. These prices, to a certain extent, reflect costs of producing a rare-earth concentrate and processing the pure compounds and must be considered approximate only. More current information on the prices of refined rare-earth oxides is not readily available. Currently, the greatest demand is for samarium and neodymium to be used in the magnet industry and for yttrium, in phosphors, engineering ceramics and superconductors (Roskill Information Services, 1988).

Cerium Subgroup (light)			Yttrium Subgroup (heavy)		
La	lanthanum	57	Y	yttrium	39
Ce	cerium	58	Tb	terbium	65
Pr	praeseodymium	59	Dy	dysprosium	66
Nd	neodymium	60	Ho	holmium	67
Pm	promethium	61	Er	erbium	68
Sm	samarium	62	Tm	thuliu	69
Eu	europium	63	Yb	ytterbium	70
Gd	gadolinium	64	Lu	lutetium	71

ZIRCONIUM AND HAFNIUM

Zirconium and hafnium are geochemically associated in zircon, which is the principal ore mineral of these elements, in a ratio of 50:1. The two elements are generally not separated, except when used in nuclear applications.

USES

Approximately 95 per cent of all zirconium consumed is in the form of zircon, zirconium oxide or other compounds. The mineral zircon is chiefly used for facings on foundry molds, for manufacture of refractory paints used to coat the surfaces of molds and to form refractory bricks that are used in furnaces and hearths that hold molten metal. It is also combined with alumina to make grinding wheels used on rough metal surfaces.

Zirconia, the oxide form, is used as an opacifier and pigment in glazes and colours for pottery and other ceramics. It is also used in the fabrication of sensors for the control of combustion of fuels in furnaces and internal combustion engines; these sensors are being installed in virtually all furnaces and new automobiles. Zirconium is used in compound form to manufacture abrasives and in such diverse products as toothpaste, glass-polishing powders, leather tanning agents, rust-inhibiting paints, water repellents for leather and textiles and, in ink to promote drying (Adams, 1985).

Zirconium metal is used as a cladding for nuclear fuel and as a structural material in nuclear reactors; it is also used in camera flashbulbs and as components in heat exchangers, acid concentrators, pipes and tubing used in the chemical industry. Zirconium-columbium alloys are used in superconducting magnets.

Hafnium is consumed primarily in the metallic form; most is used in control rods in nuclear reactors. It also goes into alloys used in gas turbine engines, gun barrels, space re-entry vehicles and chemical processing equipment. One of the fastest growing uses for hafnium is in hafnium-columbium carbide cutting tools (Adams, 1985).

OCCURRENCE-GEOLOGICAL SETTING

Zirconium is strongly concentrated in some alkaline rocks (carbonatites and syenites) and may comprise up to 2 per cent. It is also concentrated in placer deposits, in particular beach placers, as zircon is a heavy mineral with specific gravity of 4.6 to 4.7. There are no known zircon deposits in British Columbia, however, a number of the known alkaline rock complexes are enriched in zirconium (*e.g.* Trident Mountain nepheline syenite and the Lonnie carbonatite; Pell, 1987) and heavy mineral sands with ilmenite and zircon are present off shore of the Queen Charlotte Islands and north of Vancouver Island.

ECONOMICS

The major world producers of zircon are Australia, South Africa, Malaysia, Thailand, Brazil, India, China, the U.S.A., Sri Lanka and the U.S.S.R. Most zircon production is as a coproduct of titanium or rare earth mining from beach placer deposits (Adams, 1985; Garnar, 1903); minor amounts of baddeleyite are recovered as a byproduct of apatite lode mining from a carbonatite at Palabora, South Africa (Adams, 1985). Zircon concentrate (containing 65 per cent zirconia) sells for $468US per short ton, f.o.b. minesite, eastcoast U.S.A. or $570 to 700A per tonne, f.o.b. Australia. Premium grade zircon, containing a minimum of 66 per cent ZrO_2 and a maximum of 0.05 per cent Fe_2O_3, sells for $630 to 860A per tonne f.o.b. Australia (Industrial Minerals Magazine, Jan. 1990).

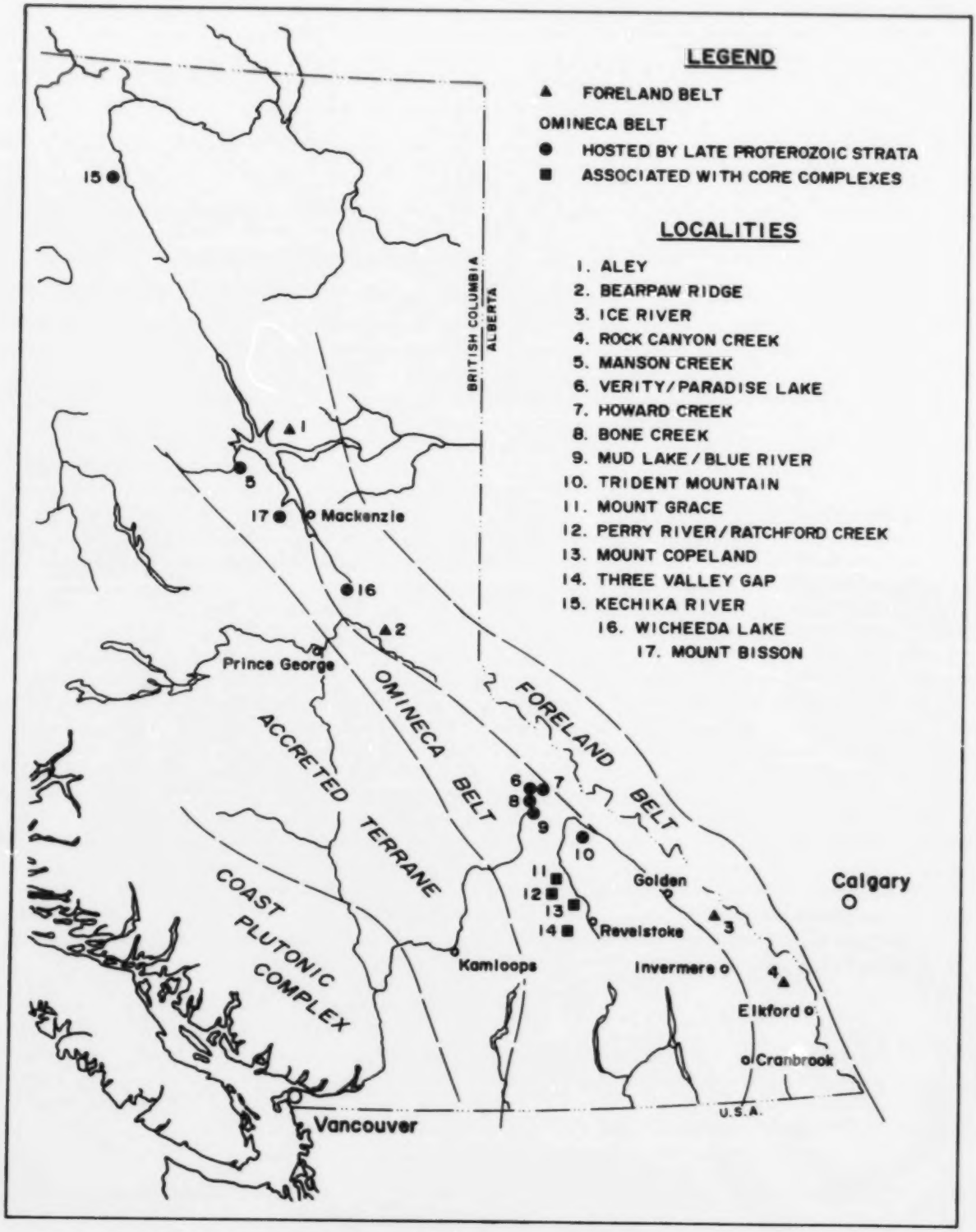

Figure 2. Locations of carbonatite and nepheline syenite complexes in British Columbia.

POTENTIAL TARGETS IN BRITISH COLUMBIA

"High-tech" elements are commonly hosted by, or associated with the rock types identical in the accompanying table. In British Columbia, a number of carbonatite-syenite complexes and volatile-rich or "specialty" granites have been discovered and others may be recognized in the future. These rocks are good exploration targets for a number of the "high-tech" elements and will be described in more detail in the following sections. Carbonate-hosted lead-zinc and volcanogenic massive sulphide deposits are present in British Columbia; some are known to have anomalous concentrations of gallium and germanium and therefore should always be analyzed for those two elements.

Peralkaline granite-syenite complexes are important in that they may host significant quantities of a number of "high-tech" metals. Copper-rich breccia pipes are important potential gallium and germanium hosts. Neither of these environments have been recognized in British Columbia; however, brief descriptions are included in this report as no *a priori* reason exists for their absence. Bauxite deposits do not occur in British Columbia; the conditions for their formation (deep tropical weathering) never existed in this part of the world. Other deposit types mentioned are less important and, while they should not be overlooked by the prospector or geologist, will not be dealt with in any detail here.

CARBONATITE - SYENITE SYSTEMS

Carbonatite/syenite complexes are mined for lanthanides, yttrium and niobium. They may also contain significant concentrations of zirconium and can be anomalous in tantalum. In Africa, Brazil and the U.S.S.R. they are also mined for associated copper, phosphate (apatite), iron and vermiculite. Nepheline syenite is quarried in Ontario for use in the glass industry (Currie, 1976). In the Jordan River area of British Columbia, northwest of Revelstoke, molybdenum associated with a nepheline syenite gneiss complex was extensively explored in the late 1960s (Fyles, 1970).

DESCRIPTION

Carbonatites are igneous rocks composed of more than 50 per cent primary carbonate minerals, predominantly calcite or dolomite. Common accessory minerals include olivine, pyroxene (often sodic), amphibole (also, often sodic), phlogopite, apatite, magnetite, ilmenite, zircon columbite and pyrochlore. Other minerals such as feldspars, fluorite and rare-earth carbonates may also be present. Carbonatites occur most commonly as intrusive bodies; they may form as dikes, sills, plugs, veins or segregations in other alkaline rocks. Less common are extrusive carbonatite flows, tuffs or agglomerates. Metasomatic rocks (fenites), which are generally enriched in sodium and ferric iron and depleted in silica, are often developed marginal to intrusive carbonatites or carbonatite complexes.

Carbonatites can be associated with nephelinite or nephelinite/nepheline syenite complexes (*e.g.* the Ice River complex near Field, B.C.; Currie; 1975, 1976), with nepheline or sodalite syenites only (*e.g.* Paradise Lake carbonatite, near Blue River, B.C.; Pell, 1987), or with weakly alkaline syenites (*e.g.* Lonnie complex, near Man-

ROCK TYPE/DEPOSIT TYPE	ASSOCIATED ELEMENTS
Carbonatite-syenite complexes	Nb, Y, REE, Zr, (Ta)
Volatile-rich granite systems	Be, Ta, Y, Ree, Nb
*Peralkaline granite-syenite systems	Be, Nb, Ta, Y, Ree, Zr, Ga
Carbonate-hosted lead-zinc deposits	Ga, Ge
Zinc-rich volcanogenic massive sulphide deposits	Ga
*Sediment-hosted, copper-rich breccia pipes and oxidized equivalents	Ga, Ge
*Bauxite deposits	Ga
Coals	Ge
Iron oxide deposits	Ge
Sedimentary phosphorites	Y

** Not known to occur in British Columbia*

son Creek, B.C.; Currie, 1976; Pell, 1987). The nephelinites associated with carbonatite complexes contain varying amounts of pyroxene (generally sodic or titanium-bearing) and nepheline. Nepheline and sodalite syenites generally contain potassium feldspar, nepheline and plagioclase feldspar with or without sodalite, with biotite or pyroxene as the common mafic phase. Weakly alkaline syenites do not contain feldspathoids. In all cases, the associated rocks are devoid of quartz as with the carbonatites.

In the field, carbonatites resemble marbles or other carbonate rocks, but in British Columbia most can be recognized by their unique orangish brown to dark reddish brown weathering colour, unusual mineral assemblage (apatite, olivine, pyroxene, magnetite, zircon, *etc.*) and anomalous radioactivity (the scintillometer is a useful prospecting tool). Other distinctive minerals such as purple fluorite may also be associated with carbonatite complexes. The most common associated igneous rock types are quartz-free syenites and nepheline or sodalite syenites which are usually white to greyish weathering. When present, nepheline can be identified in hand specimen by its slightly greyish colour and greasy lustre, while sodalite can be easily recognized by its distinctive ultramarine blue colour.

The fenites, or metasomatic alteration zones associated with intrusive carbonatite complexes, vary from being almost non-existent to forming halos extending several hundreds of metres into the hostrocks. Their nature is also highly variable, dependant on the original lithology and the composition of the fluids associated with the alkaline rocks. In general, calcsilicate and biotite-rich hostrocks are altered to sodic pyroxene and amphibole-rich rocks; quartzo-feldspathic protoliths (granites or quartz and feldspar-rich sedimentary rocks) are altered to rocks of syenitic or monzonitic composition; and carbonate hostrocks are altered to iron and magnesium-rich carbonates that may contain fluorite and rare-earth minerals.

Geochemically, carbonatites and related alkaline rocks are undersaturated with respect to silica and may contain high concentrations of elements such as strontium (generally 1000 ppm), barium, niobium and rare earths. Mineralization generally occurs in primary magmatic deposits; commonly, rare metal enriched phases, crystallized directly from the melt, occur as accessory or, less commonly, rock forming minerals.

DISTRIBUTION

In British Columbia, carbonatites, syenite gneisses and related alkaline rocks are present in a broad zone which follows the Rocky Mountain Trench. They occur in three discrete areas (Figure 2): along the western edge of the Foreland Belt, east of the Rocky Mountain Trench and immediately east of the Trench in the Cassiar Mountains (northeastern Omineca Belt); along the eastern edge of the Omineca Belt; and within the Omineca Belt in the vicinity of the Frenchman Cap dome, a core gneiss complex.

Carbonatites and related rocks in the Foreland and northeastern Omineca belts are generally present in large, multiphase intrusive and extrusive complexes with extensive metasomatic or contact metamorphic alteration halos overprinting Middle Cambrian to Middle Devonian miogeoclinal hostrocks. Carbonatites along the eastern margin of the Omineca Belt are found westward from the Rocky Mountain Trench for 50 kilometres or more. All the intrusions within this belt are hosted by late Precambrian (Upper Proterozoic) to early Cambrian metasedimentary rocks. They form foliated sill-like bodies and are associated with only minor amounts of fenitization. Along the margins of the Frenchman Cap gneiss dome, intrusive and extrusive carbonatites and syenite gneiss bodies are conformable in a mixed paragneiss succession of probable late Proterozoic to Eocambrian age (Pell and Höy, 1989; Pell, in preparation).

Alkaline igneous rocks intruding Paleozoic strata in the Foreland and northeastern Omineca belts are of Devono-Mississippian and possibly Silurian ages. Carbonatites and syenites hosted by Precambrian rocks in the eastern Omineca Belt are predominantly Devono-Mississippian. All have been deformed and metamorphosed to some degree; those in the Foreland and northeastern Omineca belts were subjected to sub-greenschist to greenschist facies metamorphism, while those elsewhere in the Omineca belt attained upper amphibolite facies (Pell and Höy, 1989; Pell, 1987, and in preparation).

Carbonatites with the best economic potential for "high-tech" elements appear to be those of mid-Paleozoic age hosted by Paleozoic sediments that are found in the Rocky Mountains and eastern Cassiar Mountains, however, carbonatites found elsewhere should not be overlooked.

VOLATILE-RICH GRANITES

In many parts of the world, "specialty" or volatile-enriched granitoids of 'topaz rhyolite' affinity are metallogenically linked to deposits of a variety of high-tech metallic and non-metallic minerals such as beryllium, yttrium, rare-earths, niobium and to deposits of tin, tungsten, molybdenum and possibly gold. Important deposit types include: Climax-type molybdenum-tungsten porphyries; silver-lead-zinc manto deposits, such as Santa Eulalia, Mexico and Midway, British Columbia; tin skarn deposits; replacement fluorite deposits, for example Las Cuevas, Mexico or beryllium deposits such as Spor Mountain, Utah.

DESCRIPTION

Volatile-enriched or "specialty" granites may be of two types. The first are generally not true granites, in the strictest petrographic sense, but are commonly alaskites (alkali feldspar granites). They have a low colour index and contain few mafic minerals; biotite is the most common and alkaline clinopyroxene (aegirine) or alkaline amphibole (riebekite or arfvedsonite) may also be present. Accessory minerals may include titanite (sphene), magnetite, apatite, zircon, allanite, fluorite, melanite garnet and monazite. Miarolitic cavities lined with quartz, feldspar, biotite, fluorite and alkaline amphiboles are commonly developed. Quartz syenites are also often present in zoned intrusions with the alaskites. Associated mineralization generally consists of one or more of molybdenum, tungsten, tin, fluorine, uranium, thorium, niobium, tantalum, yttrium or rare-earth elements in vein, greissen, skarn, porphyry or pegmatitic deposits (Anderson, 1988).

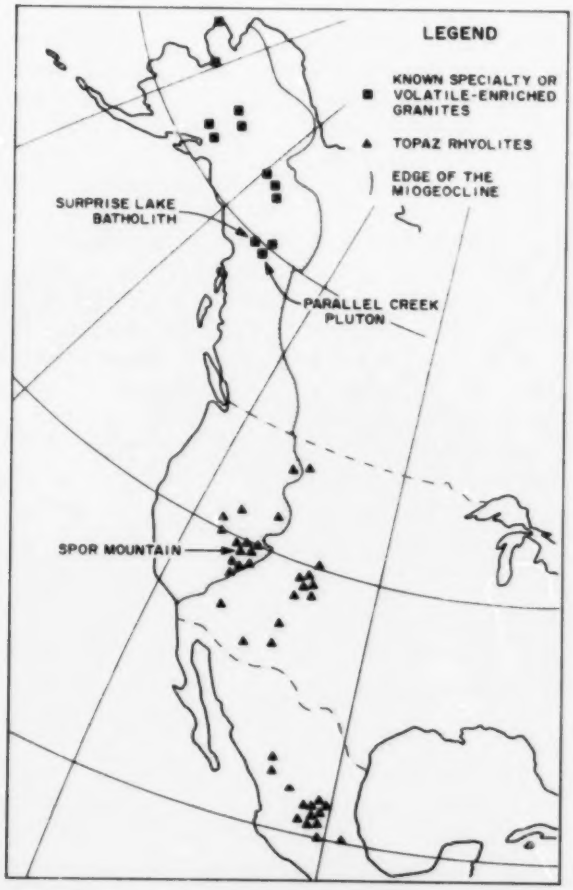

Figure 3. Distribution of specialty granites in western North America.

Two-mica granites, or more accurately, quartz monzonites may also be enriched in volatile elements. These rocks commonly have low colour indexes and contain plagioclase, potassic feldspar, quartz, muscovite, biotite and accessory tourmaline, fluorite, ilmenite, monazite and topaz. Miarolitic cavities containing quartz, feldspar and tourmaline are commonly developed. As is the case with the previous example, quartz syenites are common plutonic associates. Mineralization related to these granitic rocks may consist of tin, tungsten, copper, beryllium, zinc and, to a lesser extent, molybdenum in skarn, greissen or vein deposits (Anderson, 1988; Swanson *et al.*, 1988).

In both cases, the granitic rocks are characterized by high silica contents (SiO_2 >70 wt%), K_2O> Na_2O, relatively low TiO_2 and high concentrations of associated volatile-enriched elements such as fluorine. In general, they are peraluminous to peralkaline in composition. As well, $^{87}Sr/^{86}Sr$ isotopic ratios are commonly greater than 0.708, although the alaskites may have strontium ratios as low as 0.703. In western North America, most volatile-enriched granitoids are late Cretaceous to early Tertiary in age (Anderson, 1988; Barton, 1987).

The volatile-enriched granite environment can be most easily recognized by its geochemical signature or by the recognition of petrologic features such as miaroli cavities or accessory minerals such as fluorite. Regional geochemical surveys are a good prospecting tool; granitic bodies with associated fluorine, tin, tungsten, uranium and molybdenum anomalies are potential hosts for deposits of "high-tech" metals, particularly rare earths, yttrium, beryllium, niobium and tantalum. As previously mentioned, the deposits can occur in many forms, such as skarns, greissens, veins and pegmatites. In many cases, the mineralization is not obvious; some tin-fluorite skarns known as wrigglites (Kwak, 1987) look more like banded metasediments than conventional skarns. In exploring for these deposits any slightly unusual or altered rock should be carefully examined and, if in doubt, analyzed.

DISTRIBUTION

A well-defined belt of topaz rhyolites and specialty granites exists north and south of British Columbia within the Cordillera (Figure 3), with numerous examples in the western United States and Mexico (Barton, 1987; Burt *et al.*, 1981, 1982; Christiansen *et al.*, 1986; Ruiz *et al.*, 1985) and in Alaska and the Yukon (Anderson, 1986; Ballantyne *et al.*, 1978, 1982, 1983; Mitchell and Garson, 1981; Sinclair, 1986; Taylor, 1979). With the exception of the Surprise Lake batholith near Atlin, and the Parallel Creek batholith between Cassiar and Teslin Lake (Ballantyne and Ellwood, 1984), no examples have been documented in British Columbia. However, there are a number of indirect indicators - namely fluorine and uranium anomalies in stream waters and silts, in some

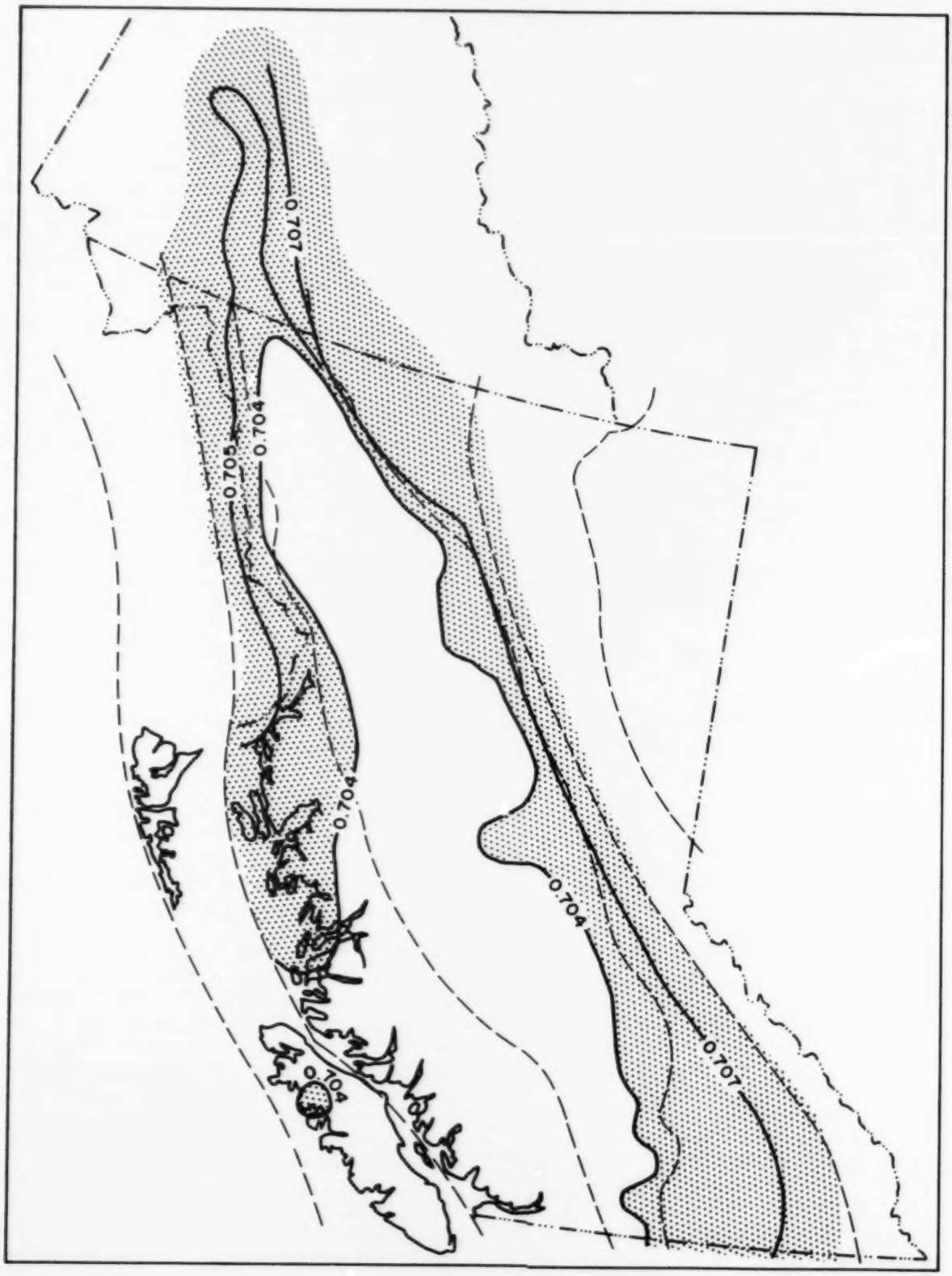

Figure 4. Map of the Canadian Cordillera showing Mesozoic $^{87}Sr/^{86}Sr$ initial ratios.

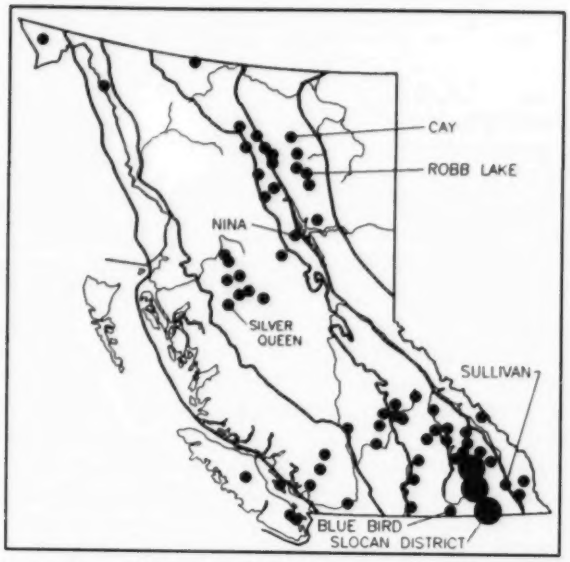

Figure 5. Location of lead-zinc deposits in B.C.

cases with coincident tin, tungsten and molybdenum anomalies, that point to the possible presence of these metallogenically important rocks in British Columbia. Isotopic evidence (Armstrong, 1985) indicates that volatile-enriched granites could possibly exist anywhere in the Cordillera where initial $^{87}Sr/^{86}Sr$ are greater than 0.704, that is areas underlain by Precambrian basement or tectonically reworked Precambrian basement or Proterozoic continent-derived clastic sedimentary rocks (Figure 4).

LEAD-ZINC-COPPER DEPOSITS

Lead-zinc-copper accumulations occur in many geological environments, forming carbonate-hosted (Mississippi Valley type) deposits, volcanogenic massive sulphide deposits (Kuroko type, Beshi type, *etc.*), sedimentary exhalative deposits (Sullivan type), skarns, mantos and veins. Trace metals, in particular gallium and germanium, can be concentrated in these deposits, commonly within the sphalerite lattice or as discrete mineral grains (*e.g.* germanite) forming inclusions within sphalerite or along sphalerite grain boundaries, however, concentrations vary greatly from deposit to deposit. Carbonate-hosted deposits, as a class, have the best potential for containing anomalous germanium concentrations. Zinc concentrates from these deposits may contain as much as 6000 ppm germanium. Individual carbonate-hosted or sedimentary exhalative deposits can be extremely anomalous with respect to gallium (in excess of 600 ppm Ga in sphalerite concentrates), but volcanogenic massive sulphide deposits, on average, have higher gallium contents (Leighton *et al.*, 1989).

It is beyond the scope of this review to deal in detail with all lead-zinc deposits. Because of the wide range of geologic environments in which they form, they are found in a variety of localities and associated with rocks of varying ages. Studies to date (Leighton *et al.*, 1989) indicate that, in British Columbia, carbonate-hosted deposits contain the greatest concentrations of gallium and germanium. These trace metal enriched deposits, for example the Cay prospect in the Robb Lake belt, are commonly characterized by the presence of distinctive reddish orange sphalerite, an abundance of pyrobitumen and silicification. Any lead-zinc-copper prospect should be checked for the presence of trace metals; elevated concentrations of elements such as gallium and germanium could potentially raise a marginal prospect to economic status.

OTHER IMPORTANT GEOLOGIC ENVIRONMENTS

PERALKALINE GRANITE - SYENITE SYSTEMS

A wide range of "high-tech" elements, including beryllium, yttrium, rare earth elements, niobium, tantalum, zirconium and gallium, are associated with peralkaline granite-syenite systems. Although they have not been recognized in British Columbia, these deposits constitute an important end-member of a spectrum of deposits related to volatile-enriched granite systems.

Peralkaline granite-syenite systems are generally characterized by complex and diverse plutonic suites (multiphase intrusions) that may consist of peralkaline granites and related pegmatites, peralkaline rhyolitic extrusives, quartz syenites, undersaturated syenites and gabbros. Mineralization may occur in primary magmatic concentrations (pegmatites and other rare metal enriched igneous phases), veins or metasomatic alteration zones. Documented peralkaline granite-syenite complexes are postorogenic and generally intrude stable cratonic environments. Two well-documented Canadian examples are the Thor Lake deposit in the Northwest Territories (Trueman *et al.*, 1986) and the Strange Lake prospect in Labrador (Miller, 1986, 1988).

SEDIMENT-HOSTED COPPER SULPHIDE BRECCIA PIPES

Sediment-hosted, copper sulphide breccia pipes and their oxidized equivalents can be the host of anomalous concentrations of gallium and germanium, and sometimes uranium. They generally consist of solution-collapse (karst) breccias in carbonate rocks that have been mineralized by later circulating fluids. In these pipes, sedimentary lithologies form angular breccia clasts while sulphides and minerals such as quartz, barite and fluorite comprise the matrix (in unoxidized pipes). In some cases the breccia clasts may be altered or partly replaced. In oxidized pipes, oxides and clay minerals dominate the breccia matrix.

Copper sulphide breccia pipes are known to occur in a number of regions in western North America including Arizona, Utah and Alaska (Bernstein and Cox, 1986; Dutrizac *et al.*, 1986; Wenrich and Sutphin, 1988). They are commonly quite small features, less than 100 metres in diameter; however, they may be as much as 800 metres across. Similar pipes have not been recognized in British Columbia, but could occur. Their small size, combined with thick cover and vegetation could make discovery difficult.

MARKETING AND ECONOMICS

Marketing is, in general, one of the most important factors in the development of "high-tech" metal resources. As is the case with many industrial mineral commodities, the problem of finding a promising prospect is often surpassed by the difficulty of finding a market; unlike gold, you cannot take it to the bank.

When considering exploration for "high-tech" metals a number of factors should be kept in mind. On the negative side: 1) on the whole, these commodities have very specialized applications and therefore limited markets or markets controlled by a small number of companies on an international level; 2) almost all applications require very small volumes of material (in most cases international consumption of these commodities is in the order of a few tens of thousands of tonnes annually); 3) most of the elements discussed here are present in trace amounts and commonly require expensive processing to recover. High unit costs commonly reflect high processing costs, not value of the commodity in the ground.

On a positive note: 1) in many cases, known producing sources are limited; 2) most forecasts are for increasing demand in known applications and, 3) the possibility exists for new uses to result from research and development efforts. Although it might appear that the negative factors outweigh the positive ones, many experts believe that there is room in the international marketplace for a small number of new producers.

A number of North American companies (or international companies working in North America) are involved in the mining, processing or exploration for "high-tech" metals, as summarized in the table below.

A number of junior companies are also involved in exploration for "high-tech" metals in British Columbia and elsewhere, including Formosa Resources Ltd. (exploring for yttrium and rare earths in B.C.), Consolidated Silver Standard Mines Ltd. (exploring carbonatites in Ontario) and many others.

The potential exists, for commercial deposits of one or more of the "high-tech" metals to be discovered and developed in British Columbia. It remains now for prospectors and geologists to make the discoveries.

COMPANY	INVOLVEMENT	AREA	COMMODITY
Teck Corporation	Mining/exploration/ property ownership	Que., B.C.	Nb, Y, REE
Cominco Ltd.	Exploration/property ownership	B.C.	Nb
Cominco Ltd.	Recovery/processing	B.C.	Ga, Ge
Hecla Mining Company	Exploration/property ownership	N.W.T., Nfld., U.S.A.	Be, Y, Nb, Ree, Zr, Ga, Ge
Molycorp Inc.	Mining/processing	U.S.A.	REE, Y
Rhône-Poulenc S.A.	Processing	U.S.A., Europe	REE, Y, Ga, Ge
Brush-Wellman Inc.	Mining/processing	U.S.A	Be
Aluminum Company of Canada Ltd.	Recovery/processing	Europe	Ga
Tantalum Mining Corporation of Canada Ltd	Mining	Man.	Ta
Highwood Resources Limited	Exploration/property ownership	N.W.T., Greenland	Be, Nb, Y, Ta, Ga, Zr
Denison Mines Ltd.	Mining/processing	Ont.	Y
E.I. DuPont de Nemours and Company	Mining/processing	U.S.A.	Zr

GLOSSARY

Alaskite: a plutonic igneous rock consisting predominantly of alkali feldspar (microcline) and quartz; plagioclase (oligoclase) subordinate; mafic constituents few or absent, also referred to as alkali granite.

Allanite: a silicate mineral belonging to the epidote group, formula: $(Ca, Ce, La)_2(Al, Fe^{3+}, Fe^{2+})_3O \cdot SiO_4 \cdot Si_2O_7 \cdot OH$. It is an uncommon accessory mineral in granites and nepheline syenites and a more common constituent of complex granite pegmatites (Phillips and Griffen, 1981).

Baddeleyite: a zirconium oxide mineral, formula ZrO_2, found in carbonatites and corundum-syenites.

Bastnaesite: a rare-earth fluorocarbonate mineral, formula $(Ce, La)CO_3F$. Found in carbonatites, complex pegmatites and contact metamorphic rocks.

Bauxite: a rock composed of the weathering products of aluminous rocks, generally hydrous aluminum oxides, formed under conditions of deep tropical weathering; principal aluminum ore.

Bertrandite: a hydrated beryllium silicate mineral, formula $Be_4Si_2O_7(OH)_2$. Found in granite pegmatites, greissens and hydrothermal veins. Principal beryllium mineral mined at Spor Mountain, Utah.

Beryl: a beryllium aluminosilicate mineral, formula $Be_3Al_2Si_6O_{18}$. Commonly green, white or yellow in colour. Gem varieties include emerald and aquamarine. Found mainly in granite pegmatites.

Beryllite: a hydrated beryllium silicate mineral, formula $Be_3SiO_4(OH)_2 \cdot H_2O$. Found mainly in cavities in pegmatites.

Carbonatite: an alkaline igneous rock composed of more than 50 per cent primary carbonate minerals.

Chalcophile: elements having a strong affinity for sulphur and concentrated in sulphide minerals (Whitten and Brooks, 1972).

Chrysoberyl: a beryllium-aluminum oxide, formula $BeAl_2O_4$. Occurs in complex granite pegmatites, contact metamorphic deposits in dolomites, fluorite skarns and highly aluminous metamorphic rocks (Phillips and Griffen, 1981).

Columbite: a niobium oxide mineral, formula $(Fe, Mn)(Nb, Ta)_2O_6$, found in granites, granite pegmatites and carbonatites.

Columbium: original name for the chemical element niobium (Nb), atomic number 41. Current usage favors niobium.

Cryogenic temperatures: very low temperatures, near absolute zero (-273°C).

Feldspathoid: a rock forming mineral similar to feldspar but containing less silica; common examples include nepheline, sodalite and cancrinite.

Fersmite: a complex hydrated niobium oxide mineral, formula $(Ca, Ce, Na)(Nb,Ti, Fe, Al)_2(O, OH, F)_6$; found in rare-earth pegmatites and carbonatites.

Germanite: a complex copper-iron-germanium sulphide mineral, formula $Cu_{11}Ge(Cu, Zn, Fe, Ge, W, Mo, As, V)_{4\text{-}6}S_{16}$. Found in copper-rich breccia pipes or associated with sphalerite in low-temperature lead-zinc-copper deposits.

Granite: a true granite, in the strictest sense, consists of 10 to 40 per cent quartz and 5 to 15 per cent mafic minerals (commonly biotite or hornblende) with feldspars constituting the remainder. Alkali feldspars plagioclase feldspars.

Greissen: a granite altered by magmatic fluids producing a rock consisting of light green (lithium) micas, muscovite, quartz, kaolinite, fluorite and topaz. Often associated with ores of tin and tungsten.

Ijolite: a plutonic rock consisting of approximately equal amounts of nepheline and pyroxene (Currie, 1976).

Jarosite: a hydrated sulphate mineral, formula $KFe_3(SO_4)_2(OH)_6$. Occurs in oxidized zones of sulphide ores and is associated with iron oxide minerals (Phillips and Griffen, 1981).

Lithophile: elements having a strong affinity for oxygen which concentrate in silicate minerals (Whitten and Brooks, 1972).

Miarolitic cavity: a small vug in a plutonic rock formed by crystallization of magma trapping a gas bubble; generally lined by late-crystallizing minerals that often display well-formed crystal shapes.

Metasomatic deposit: a deposit formed by metamorphic change involving the introduction of material (elements) from an external source.

Mischmetal: a mixture of rare-earth elements in metallic form, usually containing the same ratio of rare earth elements as found in the ore (usually 60 to 80 per cent Ce and La).

Monazite: a light rare-earth phosphate mineral, formula $(Ce, La, Th)PO_4$ found in granites, syenites and complex granite pegmatites with rare-earth minerals (Phillips and Griffen, 1981).

Nepheline: a feldspathoid mineral, formula $Na_3KAl_4Si_4O_{16}$; silica undersaturated, never occurs with quartz. Is present in alkaline igneous rocks such as syenites, ijolites and nephelinites, all of which are quartz-free.

Nephelinite: a volcanic rock essentially composed of equal amounts of nepheline and mafic silicate minerals (*e.g.* pyroxenes; Currie, 1976). The nephelinite family of rocks consists of intrusive and extrusive varieties containing varying amounts of nepheline and pyroxene (generally aegirine, although titanaugite may be present in some ultramafic varieties), lacking in feldspar, particularly plagioclase and generally poor in olivine.

Organophile: elements with a strong affinity for carbon and commonly associated with organic material.

Peralkaline: rocks in which $Al_2O_3/(K_2O + Na_2O) < 1$. The typical mafic minerals are sodic pyroxenes and sodic amphiboles (Williams, Turner and Gilbert, 1982).

Peraluminous: rocks in which $Al_2O_3/(K_2O + Na_2O + CaO) > 1$. Excess Al_2O_3 is accommodated in micas and certain minor constituents such as corundum, tourmaline and topaz (Williams, Turner and Gilbert, 1982).

Parisite: a fluorocarbonate mineral, formula $Ca(Ce, La)_2(CO_3)_3F_2$ found in alkaline pegmatites and plutons and veins.

Phenacite: a beryllium silicate mineral, formula Be_2SiO_4. Found mainly in granite pegmatites, greissens and hydrothermal veins. Principal beryllium mineral in the Thor Lake, N.W.T., high-tech metal prospect.

Phosphorite: a sedimentary phosphate deposit, generally containing greater than 18 per cent P_2O_5.

Pyrochlore: a complex, hydrated niobium oxide mineral, formula $(Na, Ca, U)_2(Nb, Ta, Ti)_2O_6(OH, F)$ found predominantly in carbonatites, alkaline intrusives and complex pegmatites.

Quartz monzonite: a plutonic rock consisting of 0 to 10 per cent quartz, 15 to 25 per cent mafic minerals (commonly biotite or hornblende) and roughly equal proportions of plagioclase and alkali feldspars.

Quartz syenite: syenite with up to 10 per cent quartz.

Refractory: resistant to heat.

Siderophile: elements with weak affinities for oxygen and sulphur, but soluble in molten iron; they are presumed to be concentrated in the earth's core and are found in metal phases of meteorites (Whitten and Brooks, 1972).

Skarn: a metasomatically altered rock formed at the contact of granitic to granodioritic intrusions by an interaction of elements from the magmatic fluids and the country rocks.

Sodalite: a feldspathoid (silica undersaturated) mineral, formula $Na_8Al_6Si_6O_{24}Cl_2$. Characterized by distinct ultramarine blue colour in hand specimen. Occurs in undersaturated alkaline igneous rocks such as nepheline syenites and phonolites.

Syenite: a group of plutonic rocks containing alkali feldspars (microcline, orthoclase), small amounts of plagioclase and hornblende and/or biotite, with little or no quartz. Silica-saturated varieties contain minor quartz, undersaturated varieties contain feldspathoids.

Xenotime: an yttrium phosphate mineral, formula YPO_4 found in granites, syenites and granite pegmatites.

Zircon: a zirconium silicate mineral, formula $(Zr, Hf)SiO_4$ commonly found in siliceous and alkaline plutonic igneous rocks (granite, diorite, syenite, nepheline syenite) and pegmatites.

REFERENCES

Adams, W.T. (1985): Zirconium and Hafnium; *in* Mineral Facts and Problems, 1985 Edition, *U.S. Department of the Interior, Bureau of Mines*, Bulletin 675, pages 941-956,

Anderson, R.G. (1988): An Overview of some Mesozoic and Tertiary Plutonic Suites and their Associated Mineralization in the Northern Canadian Cordillera; *in* Recent advances in the Geology of Granite-related Mineral Deposits, R.P. Taylor and D.F. Strong, editors, *Canadian Institute of Mining and Metallurgy*, Special Volume 39, pages 96-113.

Armstrong, R.L. (1985): Mesozoic and Early Cenozoic Magmatic Evolution of the Canadian Cordillera; manuscript submitted to Rodgers Symposium Volume.

Ballantyne, S.B., Boyle, D.R., Goodfellow, W.D., Jonasson, I.R. and Smee, B.W. (1978): Some Orientation Surveys for Uranium Mineralization in parts of the Atlin area, British Columbia; *in* Current Research Part A, *Geological Survey of Canada*, Paper 78-1A, pages 467-471.

Ballantyne, S.B. and Ellwood, D.J. (1984): An Evaluation of Reconnaissance and Follow-up Geochemical Surveys to Delineate Favorable Areas for Tin Mineralization in the Northern Canadian Cordillera; unpublished manuscript for the *International Symposium on the Geology of Tin Deposits*, Nanning City, China

Ballantyne, S.B. and Littlejohn, A.L. (1982): Uranium Mineralization and Lithogeochemistry of the Surprise Lake Batholith, Atlin, British Columbia; *in* Uranium in Granites, Y.T. Maurice, editor, *Geological Survey of Canada*, Paper 81-23, pages 145-155.

Ballantyne, S.B., Littlejohn, A.L. and Ellwood, D.J. (1983): A Tin-tungsten Multi-media Geochemical Case History: Surprise Lake Batholith, British Columbia (abstract); *Geological Association of Canada*, Program with Abstracts, Vvolume 8.

Barton, M.D. (1987): Lithophile-element Mineralization Associated with Late Cretaceous Two-mica Granites in the Great Basin; *Geology*, Volume 15, pages 337-340.

Bernstein, L.R. (1986): Gallium and Germanium Exploration Opportunities; unpublished report.

Bernstein, L.R. and Cox, D.P. (1986): Geology and Sulphide Mineralogy of the Number One Orebody, Ruby Creek Copper Deposit, Alaska; *Economic Geology*, Volume 81, pages 1675-1689.

Burt, D.B., Moyer, T.C. and Christiansen, E.H. (1981): Garnet- and Topaz-bearing Rhyolites from near Burro Creek, Mohave County, Western Arizona - Possible Exploration Significance; *Arizona Geological Society Digest*, Volume 13, pages 1-4.

Christiansen, E.H., Sheridan, M.F. and Burt, D.B. (1986): The Geology and Geochemistry of Cenozoic Topaz Rhyolites from the Western United States; *Geological Society of America, Special Paper* 205, 82 pages.

Currie, K.L. (1975): The Geology and Petrology of the Ice River Alkaline Complex; *Geological Survey of Canada*, Bulletin 245, 65 pages.

_____ (1976): The Alkaline Rocks of Canada; *Geological Survey of Canada*, Bulletin 239, 228 pages.

Dutrizac, J.E., Jambor, J.L. and Chen, T.T. (1986): Host Minerals for the Gallium-germanium Ores of the Apex Mine, Utah; *Economic Geology*, Volume 81, pages 946-950.

Fyles, J.T. (1970): The Jordan River Area, near Revelstoke, British Columbia; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Bulletin No. 57, 72 pages.

Garnar, T.E. Jr. (1983): Zirconium and Hafnium Minerals; *in* Industrial Minerals and Rocks, Volume 2, S.J. Lefond, Editor, *Society of Mining Engineers and American Institute of Mining, Metallurgical and Petroleum Engineers*, New York, pages 1433-1446.

Griffith, R.F. (1970): Columbium; *in* Mineral Facts and Problems, *U.S. Department of the Interior, Bureau of Mines*, Bulletin, pages 275-289.

Griffith, R.F. and Sheridan, E.T. (1970): Tantalum; *in* Mineral Facts and Problems, *U.S. Department of the Interior, Bureau of Mines*, Bulletin, pages 385-397.

Griffiths, J. (1984): Rare-earths - attracting increasing attention; *Industrial Minerals Magazine*, No. 199, April 1984, pages 19-39.

_____ (1985): Beryllium minerals - Demand Strong for Miniaturization; *Industrial Minerals Magazine*, No. 216, June 1985, pages 41-51.

Hendrick, J.B. (1985): Rare earth elements and Yttrium; *in* Mineral Facts and Problems, 1985 Edition, *U.S. Department of the Interior, Bureau of Mines*, Bulletin 675, pages 1-18.

Kramer, D.A. (1987): Beryllium; *in US Department of the Interior, Bureau of Mines*, Minerals Yearbook.

_____ (1988): Gallium and Gallium Arsenide: Supply, technology and uses; *U.S. Department of the Interior, Bureau of Mines*, Information Circular 9208, 25 pages.

_____ (1990): Beryllium, Gallium; *in U.S. Department of the Interior, Bureau of Mines*, Mineral Commodity Summaries.

Kwak, T.A.P. (1987): W-Sn Skarn Deposits; *Elsevier*, Amsterdam, 451 pages.

Lee, K.Y. (1970): Some Rare-element Mineral Deposits in Mainland China; *U.S. Geological Survey*, Bulletin 1312-N, 33 pages.

Leighton, D.G., Culbert, R.R. and Pell, J. (1989): Gallium, Germanium and Indium in Western Canadian Lead-zinc (Copper) Deposits (abstract); *Geological Association of Canada*, Program with Abstracts Volume 14, page A1.

Miller, R.R. (1986): Geology of the Strange Lake Alkalic Complex and the Associated Zr-Y-Nb-Be-REE Mineralization; *in* Current Research (1986), *Newfoundland Department of Mines*, Report 86-1, pages 11-19.

_____ (1988): Yttrium (Y) and other Rare Metals (Be, Nb, REE, Ta, Zr) in Labrador; *in* Current Research (1988), *Newfoundland Department of Mines*, Report 88-1, pages 229-245.

Mitchell and Garson (1981): Mineral Deposits and Global Tectonic Settings; *New York Academic Press*, 405 pages.

Mulligan, R. (1968): Geology of Canadian Beryllium Deposits; *Geological Survey of Canada*, Economic Geology Report No. 23.

O'Driscoll, M. (1988): Rare earths - Enter the Dragon; *Industrial Minerals Magazine*, November 1988, pages 21-55.

Pell, J. (1987): Alkaline Ultrabasic Rocks in British Columbia: Carbonatites, Nepheline Syenites, Kimberlites, Ultramafic Lamprophyres and Related Rocks; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Open File 1987-17, 109 pages.

_____ (in preparation): The Geology, Geochemistry and Economic Potential of Carbonatites, Nepheline Syenites, Kimberlites and Related Rocks in British Columbia; *B.C. Ministry of Energy, Mines and Petroleum Resources*.

Pell, J. and Höy, T. (1989): Carbonatites in a Continental Margin Environment - the Canadian Cordillera; *in* Carbonatites: Genesis and Evolution, K. Bell, editor, *Unwin Hyman*, London, pages 200-220.

Petkof, B. (1985a): Beryllium; *in* Mineral Facts and Problems, 1985 Edition, *U.S. Department of the Interior, Bureau of Mines*, Bulletin 675, pages 75-82.

_____ (1985b): Gallium; *in* Mineral Facts and Problems, 1985 Edition, *U.S. Department of the Interior, Bureau of Mines*, Bulletin 675, pages 291-296.

Phillips, W.R. and Griffen, D.T. (1981): Optical Mineralogy: The Non-opaque Minerals; *W.H. Freeman and Co.*, San Francisco, 677 pages.

Plunkert, P.A. (1985): Germanium; *in* Mineral Facts and Problems, 1985 Edition, *U.S. Department of the Interior, Bureau of Mines*, Bulletin 675, pages 317-322.

Richardson, Z.D.G., Sinclair, W.D., Birkett, T.C. and Trueman, D.L. (1989): High-technology Metals from a Canadian Perspective: Definition, End Uses, and Aspects of Future Demand, Supply and Marketing (abstract); *Geological Association of Canada*, Program with Abstracts Volume 14, page A1.

Roskill Information Services (1986): The Economics of Gallium, Fourth Edition; Roskill Information Services Ltd., London, 134 pages.

_____ (1988): The Economics of Rare Earths and Yttrium, Seventh Edition; *Roskill Information Services Ltd.*, London, 359 pages.

Ruiz, J., Uesler, S.E. and Jones, L.M. (1985): Strontium Isotope Geochemistry of Fluorite Mineralization Associated with Fluorine - Rich Igneous Rocks from the Sierra Madre Occidental, Mexico: Possible Exploration Significance; *Economic Geology*, Volume 80, pages 33-42.

Shannon, S.S. Jr. (1983): Rare Earths and Thorium; *in* Industrial Minerals and Rocks, Volume 2, S.J. Lefond, Editor, *Society of Mining Engineers and American Institute of Mining, Metallurgical and Petroleum Engineers*, New York, pages 1109-1118.

Sinclair, W.D. (1986): Molybdenum, Tungsten and Tin Deposits and Associated Granitoid Intrusions in the Northern Canadian Cordillera and adjacent parts of Alaska; *in* Mineral Deposits of the Canadian Cordillera, J.A. Morin, editor, *Canadian Institute of Metallurgy*, Special Volume 37, pages 216-233.

Swanson, S.E., Bond, J.F. and Newberry, R.J. (1988): Petrogenesis of the Ear Mountain Tin Granite, Seward Peninsula, Alaska; *Economic Geology*, Volume 83, pages 46-61.

Taylor, B. (1987): A Review of Beryllium: The Metal, its Oxide and Alloys; *Industrial Minerals Magazine*, April 1987, pages 67-73.

Taylor, R.B. (1979): Geology of Tin Deposits; *Elsevier*, Amsterdam, 543 pages.

Tekverk, R.W. and Fay, J.E. (1986): Gallium: An Overview, Markets, Supplies and Occurrence; *in* Geo-Expo/86, Exploration in the North American Cordillera, *Geological Association of Canada*, Cordilleran Section and *The Association of Exploration Geochemists*, pages 209-212.

Trueman, D.L. (1989): Geology of the T-Zone Rare Metal Deposit at Thor Lake, N.W.T. (abstract); *Geological Association of Canada,* Program with Abstracts Volume 14, page A1.

Wenrich, K.J. and Sutphin, H.B. (1988): Recognition of Breccia Pipes in Arizona; *Arizona Bureau of Geology and Mineral Technology*, Fieldnotes, Volume 18, No. 1, 11 pages.

Wheat, T.A. (1987): Advanced Ceramics in Canada; *Canadian Institute of Mining and Metallurgy,* Bulletin, Volume 80, No. 900, pages 43-48.

White, G.V. (1986): Preliminary Report, Lang Bay Germanium Prospect; *B.C. Ministry of Energy, Mines and Petroleum Resources*, Geological Fieldwork 1985, Paper 1986-1, pages 261-264.

Whitten, D.G.A. and Brooks, J.R.V. (1972): A Dictionary of Geology; *Penguin Books*, 516 pages.

Williams, H., Turner, F.J. and Gilbert, C.M. (1982): Petrography: An Introduction to the Study of Rocks in Thin Sections; *W.H. Freeman and Co.*, New York, 625 pages.